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# Twin Screw Extrusion of Sorghum and Soya Blends: A Response Surface Analysis

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## ABSTRACT

**Blends of sorghum and soybean flours were processed in a co-rotating twin screw extruder to prepare expanded product. Response surface methodology (RSM) was used to study the effect of soya level (SL), feed moisture (FM), barrel temperature (BT) and screw speed (SS) on extruder system parameters and physical properties of the extrudate. Response variables were product temperature (PT), motor torque (MT), specific mechanical energy (SME), expansion ratio (ER), bulk density (BD), hardness (H), crispness (C), water absorption index (WAI), and water solubility index (WSI). Second order polynomial models were developed to determine the responses as a function of process variables. *FM*, *BT*, and *SS* had a significant effect on all the responses except *BT* on *WAI*, while *SL* considerably affected *ER*, *BD*, *H, C*, and *WAI*. All the models were found to be statistically significant ($R^2$> 0.85; insignificant lack of fit). Sorghum-soya extruded product was found to be feasible and the optimum values of processing variables were: *SL*: 14 per cent; *FM:* 14 per cent wb; *BT*: 129°C; and *SS*: 422 rpm.**


**Keywords:** Extrusion, RSM, SME, Sorghum, Soybean.

## INTRODUCTION

Extrusion cooking -a high temperature/short time process- is an important food processing technique to develop products such as puffed snack and breakfast cereals (Brncic *et al.*, 2010; Mahasukhonthachat *et al.*, 2010; Santillan-Moreno *et al.*, 2011). Extrusion has been reported to be the most effective method for enhancing protein and starch digestibility of the extrudates. Additionally, it has been used to inactivate several antinutritional compounds that limit the use of grain as a staple food (Shimelis and Rakshit, 2007; Yagc and Gogus, 2008; Alex *et al.*, 2009).

Sorghum (*Sorghum bicolor*) is the fifth most important cereal crop in the world (Al-Rabadi *et al.*, 2011). India is the second largest producer and consumer in the world (Charyulu *et al.*, 2013). Sorghum is composed of carbohydrate (84.0%), protein (11%), fat (2.5%), crude fiber (2.2%), and ash (1.6%) and has an energy value of approximately 3.29 kcal $g^{-1}$ (Shobha *et al.*, 2008). Also sorghum is a potentially important source of nutraceuticals such as antioxidant phenolics and cholesterol-lowering waxes (John *et al.*, 2006). Although sorghum is nutritionally well comparable with other food grains, it has poor quality of protein, which leads to low solubility, deficiencies in essential amino acids (lysine and tryptophan), and interactions with tannin (Pelembe *et al.*, 2002; Awadalkareem *et al.*, 2008). The protein quality of sorghum can be improved by combining it with other protein-rich sources. Soybean (*Glycine max*) is an important legume, rich in quality protein (rich in lysine) and has potential to complement sorghum which is rich in sulfur containing amino acids (Pracha and Chulalak, 2000).

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Thus, the blending of sorghum and soya in appropriate proportion will make up the individual deficiencies. It has been previously reported that extruded cereal-legume products have higher protein content, high protein efficiency ratio, and improved amino acid profile (Narayan *et al.*, 2007; Alex *et al.*, 2009; Vargas-Solorzano *et al.*, 2014).

From nutritional and economic point of view, fortifying sorghum with soybean flour for the production of extruded product appears to be promising. Mainly the studies involving extrusion of sorghum-based material are focused on physical and/or nutritive properties of the expanded products. The effect of extrusion on the system parameters and functional properties of sorghum-based products has not been studied in detail. Hence, the present study was conducted to investigate the effects of feed formulation and extrusion conditions on the extrusion system parameters and physical properties of a sorghum-soya extruded product using Response Surface Methodology (RSM).

RSM is a statistical mathematical method that uses quantitative data in an experimental design to determine and simultaneously solve multivariate equations to optimize processes and products. RSM is also a useful tool to minimize the numbers of trials and provide multiple regression approach to achieve optimization (Dibyakanta and Gopirajah, 2012).

## MATERIALS AND METHODS

### Materials

Sorghum (DSV-4 variety) and Soybean (MAUS-2 variety) grains were procured from Directorate of Sorghum Research, Hyderabad, India, and AICRP on Soybean, Bangalore, India, respectively. After thorough cleaning, both sorghum and soya grains were ground to flour in a laboratory scale hammer mill, equipped with 60-mesh IS sieve.

### Extrusion Cooking

Extrusion experiments were performed on a laboratory scale co-rotating twin-screw extruder (Basic Technology Pvt. Ltd., Kolkata, India). The length to diameter ratio (L/D) was 8:1. The extruder had two barrel zones. Temperature of the first zone was maintained at 74°C throughout the experiments, whereas at the second zone (die section) was varied according to the experimental design. The circular die of 3.0 mm was used in the entire study. Blends of sorghum and soya flour were prepared as per the experimental design using a ribbon blender (GL Extrusion Systems, New Delhi, India) for 20 minutes. Simultaneously, the moisture content of the blends were also ascertained. Moisture conditioning of blends were done through moisture addition (AACC, 1983; Liu *et al.*, 2000).

Preconditioned feed mixture was metered into the extruder by a twin-screw volumetric feeder equipped with it. The speed of the feeder screw was adjusted so as to get a feed rate of 5 kg $h^{-1}$ for the entire study. Extruded samples were collected in stainless steel trays for 5 minutes after the extruder system parameters (PT and MT) reached a steady-state condition. The trays were then kept in a cabinet drier (MSW-216, Marco Scientific Works, New Delhi) at 60°C for 1 hour and cooled to room temperature. The dried samples were stored in polythene bags at room temperature (25±4°C) until analyzed. All trials were conducted in 3 replications.

### Experimental Design and Statistical Analysis

RSM was used to investigate the effects of SL and extrusion conditions on the process and product responses. The independent variables considered for this study were: Soya Level (SL): 10-30%; Feed Moisture (FM): 12-20% wb; Barrel Temperature (BT): 110-150°C, and Screw Speed (SS): 250-450 rpm. The levels of each variable were established according to the literature and preliminary

trials. Dependent variables were the product temperature (PT), motor torque (MT), specific mechanical energy (SME), expansion ratio (ER), bulk density (BD), hardness (H), crispness (C), water absorption index (WAI), and water solubility index (WSI). Central composite rotatable design was used to design the experiment. The design required 30 experimental runs (6 central, 8 axial, and 16 factorial points). Regression analysis was done to assess the effects of *SL, FM, BT* and *SS* on dependent variables. The experimental data obtained were analyzed after fitting them into a second order polynomial model

$$y_i = b_o + \sum_{i=1}^{4} b_i X_i + \sum_{i=1}^{4}\sum_{j=1}^{4} b_{ij} X_i X_j$$

Where, $X_i$, $X_iX_i$, and $X_iX_j$ are linear, quadratic, and interaction effect of the input variables which influence the response *y*, respectively, and $b_o$, $b_i$, and $b_{ij}$ are the regression coefficients to be determined. RSM was applied using a commercial statistical package, Design-Expert version 8.0.7 (Stat-Ease Inc., Minneapolis, USA), for the generation of response surface plots. The adequacy of the models was determined using model analysis, lack-of-fit test and coefficient of determination ($R^2$) analysis.

## Determination of Responses

### System Responses

PT and MT as displayed on the extruder control panel were recorded twice, in the beginning and the end of product collection. *SME* (Wh $kg^{-1}$) was calculated from the rated screw speed (1445 rpm), motor power rating (5.5 kW), actual screw speed, percentage *MT*, and mass flow rate (5 kg $h^{-1}$) using the following formula (Normell *et al.*, 2009):

$$SME = \frac{\text{actual screw speed, rpm}}{\text{rated screw speed, rpm}} \times \frac{\text{\% motor torque}}{100} \times \frac{\text{motor power rating, kW}}{\text{mass flow rate, kg/h}} \times 1000$$

### Expansion Ratio

To determine the *ER*, the cross-sectional diameter of the extrudates was determined with a digital Vernier caliper. The ratio of diameter of extrudate and the diameter of die was used to express the expansion of extrudate (Pansawat *et al.*, 2008). The *ER* values were obtained from 10 random samples for each extrusion condition.

### Bulk Density

*BD* was calculated by measuring the actual dimensions of the extrudates. After weighing the extrudate, its diameter and length were measured using a digital Vernier caliper. The *BD* was estimated using the following formula, assuming a cylindrical shape of the extrudate (Sibel and Fahrettin, 2008).

$$\text{Bulk density} = \frac{4m}{\pi d^2 1}$$

Where, *m* is mass of the extrudate (g), *d* is diameter (cm), and *l* is the length (cm). Ten pieces of extrudates were randomly selected and their average taken.

### Texture

Force-deformation data for each extrudate were obtained using a Texture Analyzer (TA HDi, Stable Micro Systems Ltd., UK) fitted with 50 kg load cell and 2 mm diameter test probe. Tests were conducted in compression mode and the probe was allowed to penetrate the product a depth of 3 mm. The peak force in N was taken as a measure of *H* (Meng *et al.*, 2010) whereas *C* was measured in terms of number of positive peaks (Subir *et al.*, 2011). The test settings included pre-test speed of 5 mm $s^{-1}$, test speed of 2 mm $s^{-1}$, and post-test

speed of 5 mm $s^{-1}$. Force-deformation curve was recorded and analyzed using an inbuilt software program. Ten randomly collected samples were measured for each extrusion condition and the mean of the observations was recorded.

### Water Absorption and Solubility Indices

*WAI* and *WSI* of extrudates were determined by a method used by Sibel and Fahrettin (2008). The extrudate samples were ground and sieved through 500 µm sieve. A 0.5 grams of sample (extrudate flour) was weighed into a centrifuge tube along with 10 mL of distilled water at 25°C and thoroughly mixed to produce a smooth dispersion. Samples were allowed to settle for 30 minutes with intermittent shaking for every 5 minutes, then, centrifuged (SIGMA 3-18K, SciQuip, UK) at 1,800×g for 15 minutes. The supernatant was decanted into a tared aluminum pan and dried to constant weight at 105°C. The weight of the gel remaining in the centrifuge tube was noted. The results were expressed as the average of two measurements.

$$\text{WAI, g/g} = \frac{\text{Weight gain by gel}}{\text{Dry weight of extrudate}}$$

$$\text{WSI, \%} = \frac{\text{Weight of dry solids in supernatant}}{\text{Dry weight of extrudate}} \times 100$$

### Optimization

Optimum values of the processing variables were obtained with the help of the numerical optimization technique of the Design-Expert software (ver. 8.0.7). The software necessitates assigning goals to the processing variables and the responses. The software was used to generate optimum processing conditions and also to predict the corresponding response.

## RESULTS AND DISCUSSION

Effects of extrusion conditions on the process and product responses are shown in Table 1. The estimated regression coefficients of the second order polynomial models for the various responses and their statistical validity defining values are reported in Table 2. The regression models for all the responses were highly significant (P< 0.01), with a high coefficient of determination ($R^2$ > 0.86). Furthermore, F-values reflected that all the models were significant. Coefficient of variation being lower than 10 per cent suggests the reasonable accuracy of the experiments and reproducibility of the models. Non significant lack-of-fit (P< 0.05) indicate that the models correlated well with the measured data.

### Process Response

### Product Temperature (PT)

The predicted response model (Table 2) indicated that the linear effects of *FM*, *BT*, and *SS*, and the quadratic effects of *BT* and *SS* were the determining factors for *PT*. Among the four variables, *BT* had a prominent effect on *PT*. The response surface plots [Figure 1, (a and b)] showed that increase in *BT* and *SS* led to an increased *PT*, whereas increase in *FM* lowered the *PT*. The interaction term *BT-SS* had a significant (P< 0.1) negative effect. *PT* values ranged between 116 and 156°C (Table 1).

*PT* plays an important role in changing the rheological properties of the extruded melts, which in turn affects the degree of expansion. The recorded temperatures were higher than the set *BT* (110-150°C), which could be due to the generation of heat through dissipation of mechanical energy during extrusion. Frame (1994) reported that the heat was generated during extrusion by inter-particulate friction, and friction between the material, the screw elements, and the barrel. Similar results were observed by Pansawat *et al.* (2008) and Meng *et al.* (2010). The significant (P< 0.05) negative effect of *FM* could be due to the reason that

**Table 1**. Effects of extrusion conditions on process and product responses.

| Extrusion condition | | | | Process responses | | | Product responses | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SL [a] (%) | FM [b] (% wb) | BT [c] (°C) | SS [d] (rpm) | PT [e] (°C) | MT [f] (%) | SME [g] (Wh kg$^{-1}$) | ER [h] | BD [i] (kg m$^{-3}$) | Hardness (N) | Crispness | WAI [j] (g g$^{-1}$) | WSI [k] (%) |
| 15 | 14 | 120 | 300 | 126 | 50.65 | 115.67 | 3.096 | 196 | 156.1 | 19.0 | 4.68 | 18.36 |
| 25 | 14 | 120 | 300 | 126 | 49.77 | 113.65 | 2.551 | 231 | 197.2 | 16.9 | 4.12 | 18.55 |
| 15 | 18 | 120 | 300 | 124 | 46.25 | 105.63 | 2.643 | 275 | 178.1 | 23.2 | 4.88 | 18.28 |
| 25 | 18 | 120 | 300 | 125 | 50.58 | 115.52 | 2.357 | 285 | 217.8 | 17.0 | 4.32 | 17.70 |
| 15 | 14 | 140 | 300 | 144 | 45.39 | 103.65 | 3.123 | 155 | 80.2 | 27.3 | 4.32 | 20.75 |
| 25 | 14 | 140 | 300 | 143 | 44.14 | 100.8 | 2.619 | 202 | 115.5 | 26.2 | 4.24 | 19.35 |
| 15 | 18 | 140 | 300 | 142 | 38.36 | 87.61 | 2.894 | 200 | 165.9 | 22.6 | 5.35 | 15.94 |
| 25 | 18 | 140 | 300 | 141 | 35.61 | 81.33 | 2.532 | 270 | 166.3 | 19.1 | 4.59 | 17.51 |
| 15 | 14 | 120 | 400 | 134 | 48.12 | 146.53 | 3.166 | 132 | 84.1 | 25.2 | 4.56 | 22.51 |
| 25 | 14 | 120 | 400 | 134 | 40.42 | 123.09 | 2.842 | 164 | 100.4 | 24.3 | 3.78 | 22.97 |
| 15 | 18 | 120 | 400 | 127 | 35.75 | 108.86 | 2.843 | 248 | 214.7 | 20.5 | 4.80 | 18.92 |
| 25 | 18 | 120 | 400 | 128 | 35.41 | 107.81 | 2.518 | 291 | 240.7 | 18.3 | 4.29 | 19.41 |
| 15 | 14 | 140 | 400 | 143 | 38.36 | 116.81 | 3.279 | 103 | 39.4 | 29.4 | 4.28 | 23.21 |
| 25 | 14 | 140 | 400 | 145 | 35.54 | 108.22 | 2.864 | 153 | 51.9 | 26.8 | 3.89 | 22.48 |
| 15 | 18 | 140 | 400 | 142 | 30.87 | 93.99 | 3.045 | 169 | 195.0 | 22.3 | 4.82 | 19.45 |
| 25 | 18 | 140 | 400 | 143 | 30.25 | 92.11 | 2.655 | 268 | 180.5 | 19.5 | 4.45 | 19.72 |
| 10 | 16 | 130 | 350 | 142 | 41.46 | 110.45 | 3.475 | 131 | 70.6 | 26.4 | 4.76 | 18.24 |
| 30 | 16 | 130 | 350 | 139 | 46.89 | 124.92 | 2.666 | 226 | 116.1 | 25.7 | 4.16 | 19.71 |
| 20 | 12 | 130 | 350 | 142 | 41.59 | 110.82 | 2.889 | 159 | 110.1 | 23.6 | 4.07 | 21.10 |
| 20 | 20 | 130 | 350 | 135 | 30.66 | 81.68 | 2.609 | 377 | 295.2 | 17.3 | 5.01 | 14.59 |
| 20 | 16 | 110 | 350 | 116 | 46.20 | 123.09 | 2.617 | 175 | 194.5 | 20.3 | 4.32 | 18.47 |
| 20 | 16 | 150 | 350 | 156 | 35.49 | 94.56 | 3.004 | 134 | 93.4 | 27.8 | 4.20 | 22.41 |
| 20 | 16 | 130 | 250 | 134 | 45.96 | 87.47 | 2.694 | 244 | 167.6 | 22.2 | 4.27 | 16.41 |
| 20 | 16 | 130 | 450 | 140 | 37.40 | 128.11 | 2.938 | 157 | 96.7 | 26.5 | 4.22 | 22.34 |
| 20 | 16 | 130 | 350 | 136 | 42.37 | 112.89 | 2.846 | 157 | 59.3 | 27.8 | 4.39 | 19.21 |
| 20 | 16 | 130 | 350 | 141 | 35.68 | 95.06 | 2.861 | 167 | 73.0 | 27.6 | 4.14 | 19.51 |
| 20 | 16 | 130 | 350 | 137 | 38.36 | 102.21 | 2.798 | 169 | 65.9 | 26.9 | 4.25 | 19.72 |
| 20 | 16 | 130 | 350 | 141 | 36.86 | 98.22 | 3.004 | 150 | 71.4 | 25.1 | 4.36 | 20.10 |
| 20 | 16 | 130 | 350 | 139 | 38.22 | 101.84 | 2.894 | 175 | 82.6 | 27.5 | 4.43 | 18.14 |
| 20 | 16 | 130 | 350 | 140 | 36.83 | 98.14 | 2.824 | 169 | 79.9 | 28.5 | 4.46 | 19.92 |

[a] Soya Level; [b] Feed Moisture; [c] Barrel Temperature, [d] Screw Speed; [e] Product Temperature; [f] Motor Torque, [g] Specific Mechanical Energy, [h] Expansion Ratio; [i] Bulk Density; [j] Water Absorption Index, [k] Water Solubility Index. Data are mean values and means from 2, 10 and 3 measurements, respectively.

**Table 2**. ANOVA and regression coefficients of the second order polynomial models of the various responses.

| Parameters | Regression coefficients PT [e] (°C) | MT [f] (%) | SME [g] (Wh kg$^{-1}$) | ER [h] | BD [i] (kg m$^{-3}$) | Hardness (N) | Crispness | WAI [k] (g g$^{-1}$) | WSI [l] (%) |
|---|---|---|---|---|---|---|---|---|---|
| Intercept | 139.00 | 38.05 | 101.39 | 2.87 | 164.5 | 72.01 | 27.23 | 4.334 | 19.433 |
| $X_1$ [a] | – 0.125 | – 0.05 | – 0.30 | – 0.2*** | 24.0*** | 10.33*** | – 0.94** | – 0.22*** | 0.092 |
| $X_2$ [b] | – 1.54** | – 2.97*** | – 8.08*** | – 0.11*** | 46.1*** | 46.00*** | – 1.88*** | 0.23*** | – 1.43*** |
| $X_3$ [c] | 8.29*** | – 3.33*** | – 8.72*** | 0.07*** | – 16.0*** | – 24.86*** | 1.82*** | 0.01 | 0.40* |
| $X_4$ [d] | 1.54** | – 3.46*** | 6.45*** | 0.08*** | – 19.2*** | – 13.01*** | 0.98*** | – 0.07** | 1.42*** |
| $X_1 X_2$ | 0.06 | 0.83 | 2.35 | 0.02 | 3.6 | – 3.36 | – 0.50 | – 0.02 | 0.20 |
| $X_1 X_3$ | – 0.06 | – 0.18 | – 0.18 | – 0.01 | 9.1** | – 5.58** | 0.089 | 0.05 | – 0.05 |
| $X_1 X_4$ | 0.31 | – 0.68 | – 2.10 | 0.01 | 3.9 | – 4.78* | 0.276 | – 0.00 | 0.04 |
| $X_2 X_3$ | 0.56 | – 0.46 | – 0.83 | 0.03* | – 5.1 | 6.69** | – 1.24*** | 0.08* | – 0.32 |
| $X_2 X_4$ | – 0.56 | – 0.69 | – 3.01 | – 0.01 | 11.1*** | 23.50*** | – 1.10** | 0.00 | –0.38 |
| $X_3 X_4$ | – 1.19* | 0.56 | 0.12 | – 0.00 | 1.1 | 3.02 | – 0.58 | – 0.03 | 0.02 |
| $X_1^2$ | – 0.05 | 1.57*** | 4.06*** | 0.04*** | 4.9* | 6.33*** | – 0.52 | 0.05 | – 0.08 |
| $X_2^2$ | – 0.55 | – 0.44 | – 1.29 | – 0.04** | 27.3*** | 33.65*** | – 1.92*** | 0.07** | – 0.30 |
| $X_3^2$ | – 1.17** | 0.74 | 1.85 | – 0.02 | – 1.08 | 18.98*** | – 1.02*** | – 0.00 | 0.35** |
| $X_4^2$ | – 0.93* | 0.95* | 1.59 | – 0.02 | 10.42*** | 16.04*** | – 0.95*** | – 0.01 | 0.09 |
| ANOVA | | | | | | | | | |
| $R^2$ | 0.94 | 0.887 | 0.86 | 0.955 | 0.973 | 0.987 | 0.908 | 0.884 | 0.890 |
| Model F-value | 18.6*** | 8.41*** | 6.87*** | 22.6*** | 38.62*** | 82.5*** | 10.6*** | 8.1*** | 8.6*** |
| Lack of fit (p value) | 0.242 | 0.311 | 0.301 | 0.536 | 0.119 | 0.3115 | 0.17 | 0.190 | 0.182 |
| C.V, % | 1.95 | 6.88 | 7.01 | 2.56 | 7.10 | 7.79 | 6.84 | 3.60 | 4.90 |

[a] Coded soya level; [b] Coded feed moisture; [c] Coded barrel temperature; [d] Coded screw speed; [e] Product Temperature; [f] Motor Torque; [g] Specific Mechanical Energy; [h] Expansion Ratio; [i] Bulk Density, [k] Water Absorption Index, [l] Water Solubility Index. * Significant at 10% (P< 0.1); ** Significant at 5% (P< 0.05), *** Significant at 1% (P< 0.01).

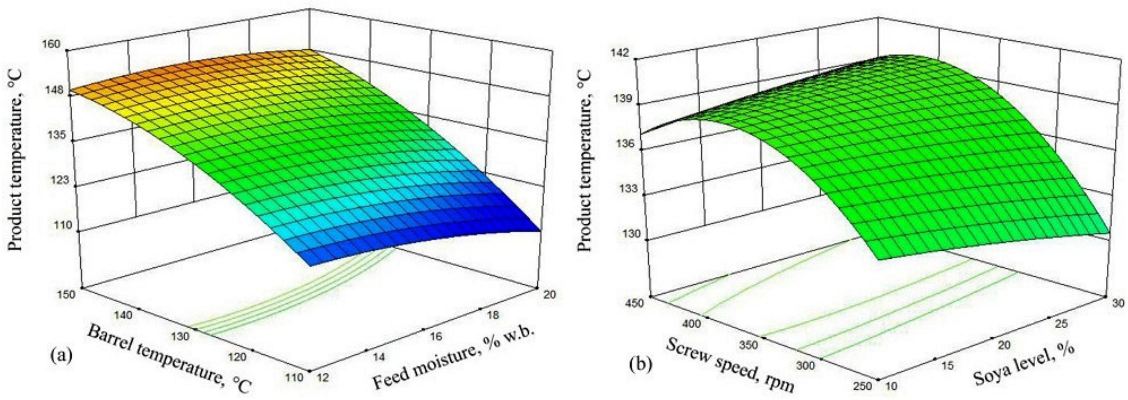


**Figure 1**. Response surface plots for *PT* as a function of (a) *BT* and *FM* (b) *SS* and *SL* while other variables are at center point

the water acts as a plasticizer in the extruder; therefore any increase in *FM* reduces the melt viscosity and dissipation of mechanical energy (Ilo *et al*., 1996). SS had a significant ($P< 0.05$) positive effect on *PT*. This may be attributed to dependence of shear or mechanical energy on *SS* (Meng *et al*., 2010). A higher screw speed generates a greater amount of mechanical energy or frictional heat and, hence, increases *PT*. Furthermore, mean residence time also influence heat generation and mass temperature. Decrease in *PT* at very high *SS* (Figure 1-b) could be due to reduced mean residence time at high SS.

## Motor Torque and Specific Mechanical Energy

*MT* provides information about the amount of energy absorbed by the material, while *SME* is the mechanical energy input per unit mass of the extrudate (Altan *et al*., 2008; Pansawat *et al*., 2008). The regression analysis results (Table 2) indicated that the liner terms of *FM* and *BT* had a significant ($P< 0.01$) negative effect on *MT* and *SME*, while SS had a significant negative effect on *MT* and positive effect on *SME*. The effect of SL was mainly quadratic ($P< 0.01$). However, interaction between the independent variables had no significant effect. The measured *MT* values ranged from 30.25% to 50.65 per cent and the calculated *SME* from 81.33 to 146.53 Wh $kg^{-1}$ (Table 1).

Any variable affecting the viscosity of the food melts in the extruder would correspondingly effect *MT* and *SME* (Akdogan, 1996). Elevating the *BT* or *FM* caused a decline in the melt viscosity, consequently, decreasing the *SME* (Figure 2) and *MT*. The degree of fill in the extruder barrel manipulates the torque requirement (Jin *et al*., 1994; Meng *et al*., 2010). At a constant feed rate, an increase in *SS* decreased the length of filled flights resulting in reduced load on the screw shaft thereby lowering the *MT* (Figure 3). Although a decrease in *SME* was expected as melt viscosity would decrease with increasing SS, the present study indicates that the effect of *SS* dominates the effect of melt viscosity. This could be attributed to the increased shear rate with increase in *SS* and is a well-documented observation in various studies (Akdogan, 1996; Altan *et al.*, 2008; Normell *et al*., 2009). The significant effect ($P< 0.01$) of quadratic term of *SL* on *MT* and *SME* implies a considerable increase in these two responses after a certain level of soya. This is also reflected on the surface plot (Figure 3) with a curved surface. This result revealed that the viscosity effect, at lower levels of soya, was dominated by the

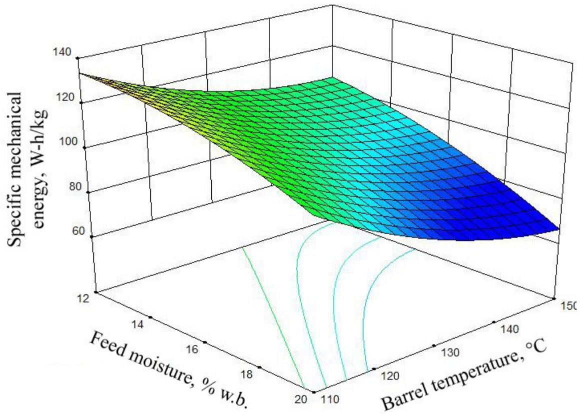


**Figure 2**. Response surface plot for *SME* as a function of *FM* and *BT* while other variables are at center point.

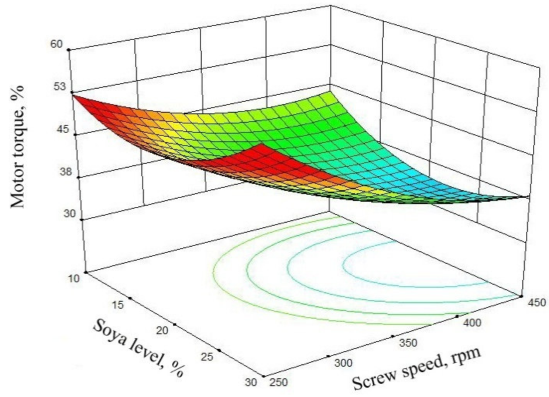


**Figure 3**. Response surface plot for *MT* as a function of *SL* and *SS* while other variables are at center point.

binding action of high protein content in the feed blend at high *SL*.

## Product Response

### Expansion Ratio and Bulk Density

*ER* and *BD* describe the degree of expansion undergone by the melt as it exits the extruder, while *ER* considers expansion only in the direction perpendicular to the extrudate flow, *BD* considers expansion in all directions (Altan *et al*., 2008). The regression results (Table 2) indicated that all the investigated variables had a significant (P< 0.01) effect on *ER* and *BD*. *ER* was significantly affected by the quadratic term of *SL*, while *BD* by *BT* and *SS*. Interaction terms of *SL-BT* and *FM-SS* were found to be significant on *BD*. The *ER* of extrudates varied between 2.357 and 3.475, while *BD* varied between 103 and 377 kg m$^{-3}$ (Table 1).

The significant effect of *FM* on *ER* and *BD* could be due to either changed molecular structure of amylopectin, which reduces the melt elasticity (Ilo *et al.*, 1996), or extrusion cooking is not enough to cause vaporization of moisture resulting in reduced expansion and increased density (Asare *et al*., 2012). Increase in *BT* increased *ER* while reducing *BD*, probably due to enhanced gelatinization of starch, which increases the volume of extrudates (Case *et al*., 1992). In addition, high temperature provides higher potential energy for flash-off of super-heated water from extrudates with increased linear velocity at the die favoring expansion (Koksel *et al*., 2004). At low moisture levels, *ER* increased with *BT* before it reached a critical level after which it declined (Figure 4). This may be caused by dextrinization of starch and weakening of structure (Dogan and Karwe, 2003). *ER* decreased and *BD* increased with increase in *SL*. This could be attributed to the dilution effect of soya on starch, which may affect the extent of starch gelatinization and, thus, the rheological properties of the melted material (Sibel and Fahrettin, 2008). The significant (P< 0.01) negative effect of *SS* on *BD* (Figure 5) and *ER* could be attributed to the structural breakdown under increased shear environment. Increasing *SS* tends to increase the shearing effect, this causes protein and starch molecules to be stretched farther apart, weakening bonds and resulting in a puffer product (Filli *et al*., 2012). The effect of *FM* and *SS* were found to be dependent on each other (Table 3). Similar results have been reported earlier for different types of the extruded products

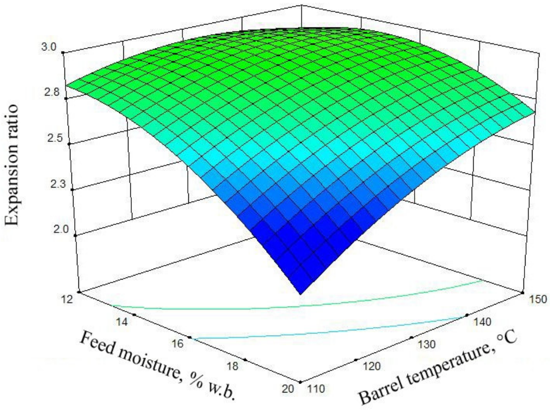


**Figure 4**. Response surface plot for *ER* as a function of *FM* and *BT* while other variables are at center point.

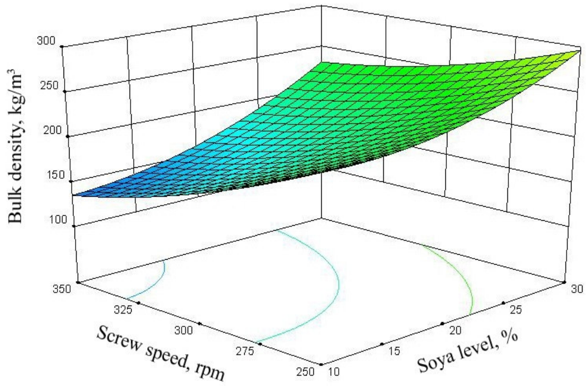


**Figure 5**. Response surface plot for *BD* as a function of *SS* and *SL* while other variables are at center point.

(Meng *et al*., 2010, Asare *et al*., 2012; Filli *et al*., 2012).

## Hardness and Crispness

Hardness (H) of the expanded extrudates is a sensory perception of the human being and is associated with expansion and cell structure of the product, while crispness (C) is typically a textural attribute (Meng *et al*., 2010). *H* and *C* were significantly (P< 0.01) affected by the linear terms of all predictor variables. Increasing *SL* and *FM* and decreasing *BT* and *SS* significantly increased *H*, while reducing *C* (Table 2). The variables also had a significant quadratic effect (P< 0.01) on *H* and *C*, except *SL* on *C*. Comparing the regression coefficients, it was observed that the *FM* had a maximum influence on *H* and *C*, followed by the *BT*, *SS*, and *SL*. Hardness of the extrudates varied between 39.4 and 295.2 N, while *C*, as the number of positive peaks, ranged between 16.9 and 29.4 (Table 1).

Chang *et al*. (1998) suggested that the degree of expansion affects density, fragility, and softness of the extruded products. *H* increased (Figure 6) and C decreased with increase in *SL* and *FM*. This is in agreement with the degree of cooking, as indicated by *ER* in this study. Increasing *SL* and *FM* decreased the degree of starch gelatinization and, as a result, pore wall became thicker and hard and heavy product was obtained (Adrian *et al.*, 2008). This result is in consistent with those of Liu *et al.* (2000), Li *et al.* (2005) and Normell *et al.* (2009). The significant (P< 0.01) negative effect of *BT* on *H* is in line with the *BD*, where an increase in *BD* was observed (Table 2). Ding *et al.* (2005) reported that the increase in *BT* would decrease the melt viscosity, but increases the vapor pressure of water which favors the bubble growth and, consequently, expansion. Thus increase in *BT* resulted in a soft and crispy product. Similar results were reported by Altan *et al.* (2008). Increase in *SS* increased *C* (Figure 7) while reducing *H*. This may be attributed to the relative increase in the amount of mechanical energy delivered to the extruded material at higher *SS*. In this study, this could be explained by the significant positive influence of *SS* on *SME* (Table 2). This increased mechanical energy delivered to the material at higher *SS* might have enhanced starch conversion, leading to crispier product (Meng *et al*., 2010). The interaction between *FM* and *SS* was significant (P< 0.01), which means that the higher values of *H* at high levels of *FM* were dependent on *SS*. Similar effect of *SS* has been observed in corn (Altan *et al*., 2008), barley (Liu *et al*., 2000) and chickpea (Meng *et al*., 2010) based extrudates.

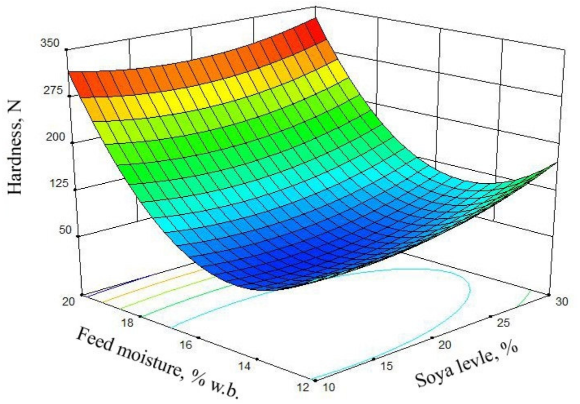


**Figure 6**. Response surface plot for hardness as a function of *FM* and *SL* while other variables are at center point.

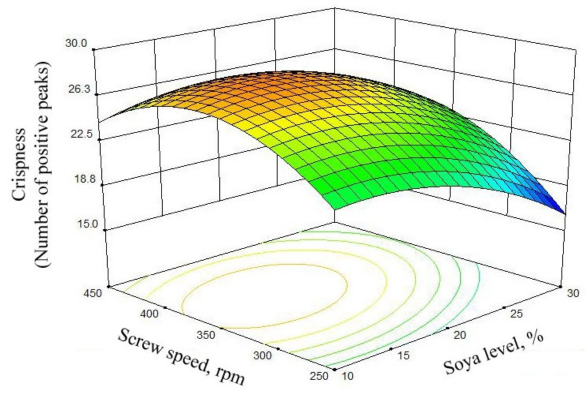


**Figure 7**. Response surface plot for crispness as a function of *SS* and *SL* while other variables are at center point.

## Water Absorption and Water Solubility Indices

*WAI* and *WSI* are two important measures related to the degree of starch conversion or damage as a result of extrusion processing (Normell *et al.*, 2009). *WAI* measures the amount of water absorbed by starch and can be used as an index of starch gelatinization, while *WSI* indicates degradation of starch molecules (Sibel and Fahrettin, 2008). The statistical analysis demonstrated that linear terms of *SL, FM* and *SS* had a significant effect on the *WAI* and *WSI*, with the exception of *SL* on *WSI*. The interaction between the variables had no significant effect, except *FM* and *BT* interaction on *WAI* ($P < 0.1$). The quadratic terms of *FM-BT* had a significant ($P< 0.05$) positive effect, respectively, on *WAI* and *WSI*. The value of *WAI* ranged between 3.78 and 5.35 g $g^{-1}$ dry sample, while *WSI* varied between 14.59 and 23.21% (Table 1).

The *WAI* decreased significantly ($P< 0.01$) as *SL* increased (Figure 8), mainly because of reduction in the starch content. Relative decrease in starch content with addition of soya may affect the extent of starch gelatinization in barrel and caused reduced water absorption. Similar effects of adding non-starch components on *WAI* have been reported earlier for millet-legume blend (Subir *et al.*, 2011). It is generally agreed that *FM* exerts the greatest effect on the extrudate by promoting gelatinization (Ding *et al.*, 2005). At high moisture content, the viscosity of the starch would be low, which allows extensive internal mixing and uniform heating that would account for enhanced starch gelatinization while diminishing starch degradation (Miranda *et al.*, 2011). Further, low moisture conditions results in greater shear degradation of starch during extrusion (Anastase *et al.*, 2006). Therefore, *WAI* increased and *WSI* decreased with increase in *FM*. Similar effects were reported earlier for rice based extrudates (Ding *et al.*, 2005). The significant ($P< 0.05$) negative effect of SS on *WAI* suggests that higher SS degraded starch into smaller fragments, which are more soluble in water. High input of thermal energy due to high residence time (at low SS) may enhance starch degradation and increase *WSI* (Figure 9). The effect of *SS* on molecular degradation and gelatinization of starch is in agreement with van den Einde *et al.* (2004) and Normell *et al.* (2009). WSI is reported to be related to the presence of soluble molecules that have sometimes been

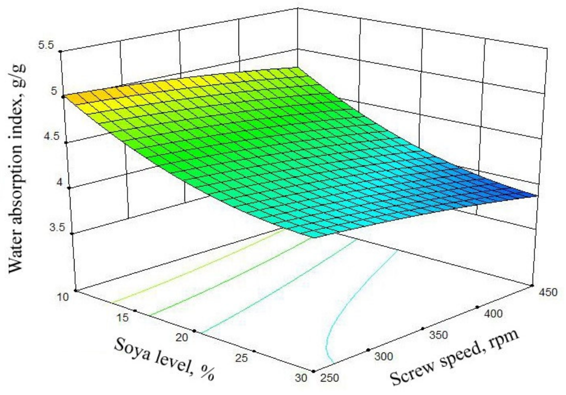


**Figure 8**. Response surface plot for *WAI* as a function of *SL* and *SS* while other variables are at center point.

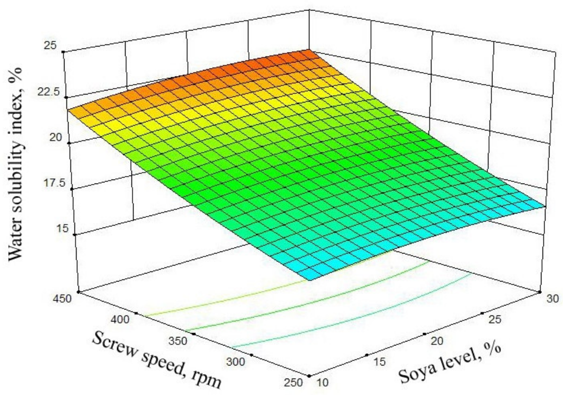


**Figure 9**. Response surface plot for *WSI* as a function of *SS* and *SL* while other variables are at center point.

attributed to dextrinization (Anastase *et al.*, 2006). The significant (P< 0.05) quadratic positive effect of *BT* on *WSI* could be probably due to increased dextrinization at higher *BT*.

## Optimization

Optimization was carried out under the following constraints: maximize soya level, *ER*, *SME, C, WAI*, and *WSI*; minimize *BD* and *H*. The optimum conditions obtained for *SL, FM, BT*, and *SS* were 14 per cent, 14 per cent wb, 129°C and 422 rpm, respectively. The corresponding optimum values of *ER, SME, C, WAI, WSI, BD* and *H* were 3.319, 140 Wh $kg^{-1}$, 27, 4.33 g $g^{-1}$, 23.45 per cent, 102.2 kg $m^{-3}$, and 42 N, respectively.

## CONCLUSIONS

This study analyzed the effect of processing variables on the responses of extrudates manufactured from different blends of sorghum and soybean. The models were found to be statistically valid and provided adequate information regarding the behavior of the responses upon variation in the processing variables. The results showed that various levels of soybean could be incorporated into extruded sorghum based snacks depending on the desired qualities of the product. The products with high *ER* and *C* and low *BD* and *H*, which are generally good characteristics of extruded snacks, were produced at low *FM*, high *SS*, medium to high *BT*, and medium *SL*. The study confirms the feasibility of developing nutritious snack food from sorghum-soya by extrusion processing.

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# خروجی مخلوط سورگم و سویا از دستگاه روزن ران مضاعف: تجزیه به روش سطح واکنش

ت. و. آرون کومار، د. و. ک. ساموئل، س. ک. جها، و ج. پ. سینها

## چکیده

برای تولید یک محصول، مخلوط آرد سورگم و سویا در یک دستگاه اکسترودر یا روزن ران مضاعف(twin screw extruder) و همچرخ فرآوری شد. برای بررسی اثرهای مقدار سویا(SL)، رطوبت خوراک(feed moisture (FM) )، درجه حرارت بشکه(BT) ، و سرعت پیچ(SS) ،روی پارامترهای دستگاه و ویژگی های مواد خروجی از دستگاه مزبور از تجزیه به روش سطح واکنش (Response surface methodology) استفاده شد. متغیر های واکنش (پاسخ) عبارت بودند از حرارت محصول(PT)، گشتاور موتور(MT)، انرژی مکانیکی ویژه(SME)، جرم مخصوص (BD)، سفتی(H)، تردی و شکنندگی(C)، نمایه جذب آب(WAI)، و نمایه حلالیت در آب(WSI). سپس به منظور تعیین واکنش ها به صورت تابعی از متغیر های فرآیند فرآوری، ازمدل چند جمله ای درجه دوم استفاده شد. نتایج نشان داد که BT،FM ، و SS اثرهای معنی داری روی همه واکنش ها داشتند به استثنای اثر BT روی WAI ، در حالی که SL به گونه ای چشمگیر روی C، H، BD،ER و WAI اثر گذاشت. همه مدل ها از نظر آماری معنی دار بودند ($R^2 > 0.85$، نا برازش معنی دار نبود). بنا بر نتایج، مخلوط سورگم-سویای حاصله از دستگاه روزن ران محصولی قابل تولید بود و مقدار بهینه متغیر های فرایند فرآوری به این قرار مشخص شد:SL=٪۱۴ ، مبنای تر FM=٪۱۴ ، حرارت بشکه برابر C° ۱۲۹ و SSمعادل ۴۲۲rpm.